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Variations of compound precipitation and temperature extremes in China during 1961–2014

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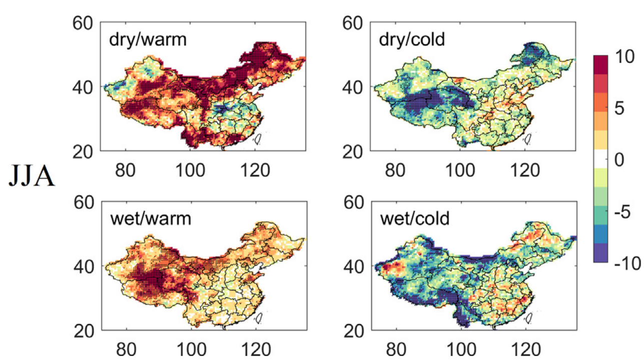
HIGHLIGHTS

- The frequency and spatial extent of compound extremes has changed over China.
- The dry/warm and wet/warm occurrences increased in most parts of China.
- The dry/cold and wet/cold occurrences decreased in most parts of China.
- The spatial extent of the warm (cold) mode showed an increase (decrease).

GRAPHICAL ABSTRACT



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ABSTRACT

Concurrent precipitation and temperature extremes usually have significant impacts on the society, economy and ecosystem. Changes in precipitation or temperature extremes in China have been extensively studied; however, less attention has been paid to their concurrence (or compound extremes) to date. This study explores the historical variations of compound extremes including dry/warm, dry/cold, wet/warm, and wet/cold combinations based on monthly precipitation and temperature observations during summer and winter from 1961 to 2014 over China. Results show that there is a significant increase in the frequency of compound dry/warm and wet/warm extremes while a decrease in compound dry/cold and wet/cold extremes for the period 1988–2014 relative to 1961–1987. In addition, statistically significant increase in the spatial extent exists in compound dry/warm and wet/warm extremes, while the areas affected by the compound dry/cold and wet/cold extremes present a decrease across China, which is shown to be partly related to the large-scale circulation patterns. The results of this study could improve our understanding of changes of compound precipitation and temperature extremes from a multivariate perspective.

1. Introduction

Weather and climate extremes, such as droughts, floods, heat waves, and cold waves, have large impacts on the ecosystem, agriculture, and human health (Ciais et al., 2005; Schmidli and Frei, 2005; Benestad and Haugen, 2007; Allen et al., 2010; Bandyopadhyay et al., 2012). The concurrent or consecutive extremes, such as the concurrent dry and heat wave during 2003 in Europe, often have more severe and disproportionate impacts on environment and human systems than individual extremes (Leonard et al., 2014; Martius et al., 2016; Zhang et al., 2018; Liu et al., 2018). The concurrent or consecutive occurrence of multiple extremes (events) is commonly termed as compound extremes (events) and has attracted much attention in the past decade due to

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the amplified impacts (Zscheischler et al., 2018). Extremes related to precipitation and temperature, which are among the most important variables in climate science and hydrology, have been commonly studies to evaluate the variability of compound extremes. Typically, the compound drought and hot extreme (or heatwave) has been shown to cause disastrously environmental and social impacts, such as hitting crop yield (Ciais et al., 2005), increasing tree mortality (Allen et al., 2010), and affecting human health (Bandyopadhyay et al., 2012). Other compound extremes, such as the concurrence of heavy rainfall and high temperature (wet/warm) in spring that can lead to flooding in some regions (e.g., Scandinavia and Norway), may also cause detrimental effects on society (Schmidli and Frei, 2005; Benestad and Haugen, 2007). Therefore, a deep understanding of variations of different types of compound precipitation and temperature extremes is essential to adopt appropriate strategies to reduce potential impacts on the society and ecosystem.

Precipitation and temperature are closely associated with a variety of extremes including hot extremes, cold spells, floods, droughts and so on. The correlation between precipitation and temperature has been addressed at different scales for various regions in many studies (Trenberth and Shea, 2005; Adler et al., 2008; Liu et al., 2012; Fernandez-Montes et al., 2017). There is a positive correlation between precipitation and temperature at high latitudes in winter, whereas a strong negative correlation is dominant in the warm season in most of the world's land areas (Trenberth and Shea, 2005; Adler et al., 2008). Hence, heavy rainfall often occurs with high temperature (or low rainfall occurs in cold conditions) in winter in some high latitudes (Tencer et al., 2014), while the occurrence of precipitation deficits is often accompanied by high temperature extremes (or heavy precipitation occurs in cold day) in the warm season in most continental land areas (Mueller and Seneviratne, 2012; Tencer et al., 2014). Due to their severe impacts, compound precipitation and temperature extremes have received an increasing attention (Beniston, 2009; Hao et al., 2013; Martin and Germain, 2017), which are usually investigated based on four combinations, i.e., dry/warm, dry/cold, wet/warm, and wet/cold. For example, Beniston (2009) analyzed the concurrent precipitation and temperature extremes in Europe based on cool/dry, cool/wet, warm/dry and warm/wet combinations and showed significant decrease in frequency of cold modes while sharp increase in warm modes. Martin and Germain (2017) investigated the relationship between avalanche and weather patterns in White Mountains under the four joint modes and revealed different avalanche activity with different modes. Similarly, Hao et al. (2013) examined the changes of joint precipitation and temperature extremes using the same four combinations on a global scale. In addition, Tencer et al. (2014) assessed the variations of wet/warm and wet/cold modes in Canada and Sedlmeier et al. (2018) mainly focused on dry/hot extremes over central Europe. These studies generally presented substantial increases in compound extremes related to the warm mode.

China has a complicated and diverse climate, making its economic and social development vulnerable to the impacts of climatic extremes. Recently, a multitude of studies have been devoted to the variations of precipitation and temperature extremes in China (Sun et al., 2014; Miao et al., 2015; Zhou et al., 2017; Shi et al., 2018a; Shi et al., 2018b; Li et al., 2018; Yao et al., 2018; Tong et al., 2019). For example, Miao et al. (2015) and Li et al. (2018) investigated the precipitation extremes over China, and showed that the precipitation extremes could increase in most regions over China under global warming (Li et al., 2018). Sun et al. (2014) and Shi et al. (2018a) assessed the temperature extremes in China, and found that there was a significant increase in hot extremes while a decrease in cold extremes. In addition, according to Shi et al. (2018b), who investigated the consecutive precipitation and temperature extremes in China, warm days increased in most parts of China while cold days decreased in almost all parts of China. Numerous studies by far usually focus on univariate analysis of precipitation or temperature, even though multiple variables are considered (Lou et al., 2017; Shi et al., 2018b). However, the past decades have witnessed a variety of compound precipitation and temperature extremes in China, such as the compound drought and hot event in 2006 in southwest China, which led to unprecedented impacts to the society and ecosystems (Wang et al., 2015). Up to now, the exploration of compound precipitation and temperature extremes in China has been limited but increasing. For example, Qian et al. (2014) investigated the compound wet/cold events and highlighted that they mostly occurred in southern China. Yuan et al. (2016) assessed the concurrent drought and heatwave during 2013 in southern China. Nevertheless, a systematic evaluation of the variations of different types of compound precipitation and temperature extremes over China has been rather limited.

The objective of this study is to investigate changes in the frequency and spatial extent of compound precipitation and temperature extremes of dry/warm, dry/cold, wet/warm, and wet/cold combinations during summer (June, July and August, JJA) and winter (December, January and February, DJF) in China based on the monthly precipitation and temperature datasets over the period 1961–2014. The influence of large-scale atmospheric circulation patterns on the spatial extent of these compound extremes is also explored. Results from this study show substantial changes of compound extremes over the whole nation which may be useful for making strategies on climate change to reduce their impacts.

2. Data

In this study, the compound precipitation and temperature extremes were computed based on monthly precipitation and temperature data (0.5° spatial resolution) from 1961 to 2014, which were obtained from the National Meteorological Information Center, China Meteorological Administration and covered 2472 meteorological stations across the whole nation. The monthly precipitation and temperature data are available at http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_PRE_MON_GRID_0.5.html and http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_TEM_MON_GRID_0.5.html, respectively. Following previous studies in defining compound extremes (or events) (Beniston, 2009; Hao et al., 2013), we used the 25th and 75th percentiles of precipitation and temperature for each month of the two seasons JJA and DJF for the whole study period 1961–2014 as the thresholds. Specifically, for each month, the wet extreme occurs when the precipitation is higher than 75th percentile while the dry extreme occurs when the precipitation is lower than 25th percentile. Similarly, the warm extreme occurs when the temperature is higher than 75th percentile, while the cold extreme occurs when the temperature is lower than 25th percentile. The occurrence of compound precipitation and temperature extreme here is denoted as the case of two extremes occurring at the same month. We also used different thresholds of precipitation and temperature (i.e., 40th and 60th percentiles, 10th and 90th percentiles) to define compound extremes and consistent patterns of changes were obtained (not presented). We only focus on the results based on 25th and 75th percentiles in the following sections.

In addition, climate indices of several large-scale circulation patterns were used to assess their potential impacts on compound extremes. Time series of these indices including Arctic Oscillation (AO), El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), and Pacific Decadal Oscillation (PDO) were obtained from https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/. In addition, monthly indices of the East Atlantic/Western Russia (EA/WR) pattern were obtained from https://www.cpc.ncep.noaa.gov/data/teledoc/eawruss.shtml. These large-scale circulation patterns have been shown to affect the climate in China (or Asia) and will be used to explore the relationship between the large-scale mode of climate variability and the spatial extent of the compound extremes.

3. Results

3.1. Frequency of compound extreme

The frequency of compound extremes is defined as the total number of months with concurrent extremes during the period of interest. The frequency of the four compound extremes during JJA and DJF for the whole period from 1961 to 2014 is shown in Fig. 1. During JJA, the compound dry/warm (wet/cold) extreme occurred highly in most regions across China except for some parts of Qinghai-Tibet region, while for the compound dry/cold and wet/warm extremes, the pattern was the opposite. The pattern of the occurrence frequency of compound extremes can be partly explained by the correlation between precipitation and temperature (Zhou and Liu, 2018). To illustrate this point, the correlation coefficients between precipitation and temperature during JJA and DJF for the period 1961–2014 are shown in Fig. 2 (dotted regions indicate significant correlation at the 0.05 significance level). For example, if a negative correlation exists between precipitation and temperature, the occurrence of compound dry/warm or wet/cold extremes is expected to dominate. This explains the higher frequency of the compound dry/warm and wet/cold extreme in southern China, where the significant and negative correlation between precipitation and temperature exists. Similarly, the low frequency of compound dry/warm and wet/cold extremes in some parts of Qinghai-Tibet region in JJA is related to the positive correlation between precipitation and temperature in this region.

For the compound dry/warm and wet/cold extreme during DJF, high frequency was observed over large regions, including certain regions in southwestern and northwestern China (with significant and negative correlations between precipitation and temperature). Along with the positive correlation between precipitation and temperature in parts of northern China and southeastern China, these regions showed relatively high frequency of compound dry/cold and wet/warm extremes compared with other regions. These findings indicate that higher frequency of compound dry/warm and wet/cold extremes exists during both warm and cold seasons than that of compound dry/cold and wet/warm extremes over the country. These results are generally consistent with the findings of Zhou and Liu (2018), in which similar patterns of the likelihood of compound hot/dry and hot/wet events in JJA and compound cool/dry and cool/wet events in DJF were shown based on statistical models.

3.2. Changes in the frequency

For each grid point, the changes in the frequency are defined as the difference in the frequency of concurrent extremes during 1988–2014 relative to that during 1961–1987 (Fig. 3). The significance of the difference between the occurrence of compound extremes for the two periods was assessed based on a two-sample t-test (Wilks, 2011) (dotted regions in Fig. 3 indicate significant difference at the 0.05 significance level). For warm season (JJA), the occurrence of the compound dry/warm extreme has presented a significant increase in the period 1988–2014 relative to that of 1961–1987 in many regions except for some areas in northwestern, eastern and central China. The decrease in the compound dry/warm extreme in these regions may be partly due to the effect of decrease in summer mean temperature (Wang et al., 2014) and increase in precipitation (both extremes and summer total rainfall) (Zhai et al., 2005; Lu et al., 2014). Additionally, the compound wet/warm extreme has presented an increase in almost all parts of China. Conversely, the compound dry/cold and wet/cold extreme has decreased in large parts of China. The significant decrease of the compound dry/cold extreme was shown in Qinghai-Tibet region and certain northeastern regions while that of the compound wet/cold extreme was mostly shown in southwestern region and certain parts of northern China.

For cold season (DJF), the compound dry/warm and wet/warm extremes have increased in 1988–2014 relative to that in 1961–1987 for most parts of China and the increase was significant in large regions. Previous studies have shown increased hot days and decreased cold days largely in winter in recent decades across China (Wu et al., 2017). Similar to the changes in JJA, these results may mainly be attributed to the variations of temperature(i.e., general increase in temperature resulted in the increase in warm days and decrease in cold days in winter over the whole China (Piao et al., 2010)). Compared to that in JJA, the frequency of compound dry/cold extremes in DJF decreased for larger regions and change of the compound wet/cold extreme showed less spatial continuity and concentration with significant changes in limited regions.

3.3. Changes in the spatial extent

The spatial extent is defined as the proportion of area covered by different compound extremes, which was computed based on the average number of grid points with compound extremes per season (i.e., JJA or DJF) divided by the total number of grid points of China. We further explored the changes in the spatial extent of the four compound extremes during JJA and DJF for the full period 1961–2014 (Fig. 4). The non-parametric Mann-Kendall test was applied for the trend test of the spatial extent of compound precipitation and temperature extremes (at the 0.05 significance level). The test results of the p-value and the slope value are also displayed in Fig. 4. During JJA, the spatial extent of compound dry/warm and wet/warm extremes has increased at a rate of 0.02 and 0.01 per decade, respectively. For the compound dry/cold and wet/cold extreme, there was a significant decrease in the spatial extent at the same rate of 0.01 per decade. All these changes have passed the significant trend test at the 0.05 significance level. During DJF, the changes in both dry/warm and wet/warm combinations have presented a significant increase at the same rate of 0.02 per decade at the 0.05 significance level. In contrast, the dry/cold combinations displayed a significant decrease in the spatial extent at a rate of 0.02 per decade. For the

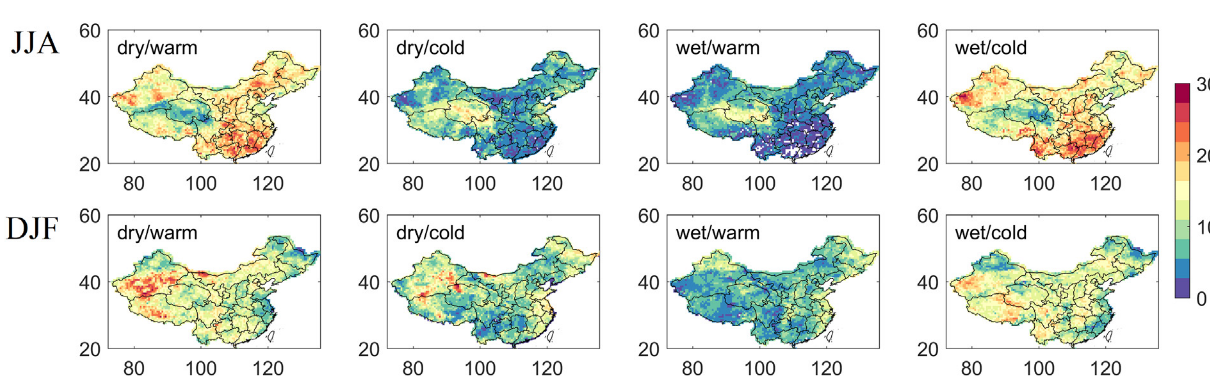

Fig. 1. Frequency (months) of compound precipitation and temperature extremes during JJA and DJF for the period 1961–2014 in China.

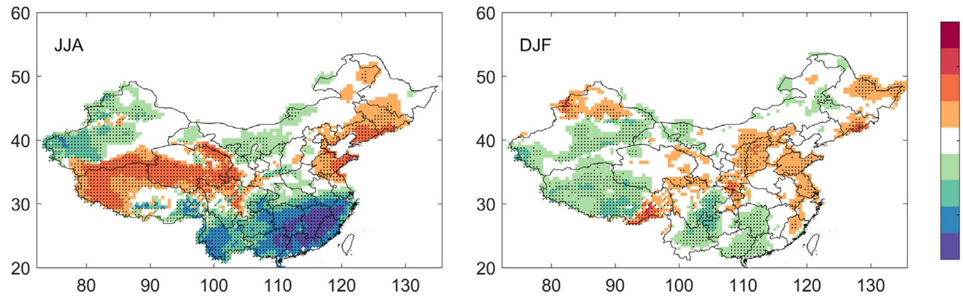

Fig. 2. Correlation coefficients between precipitation and temperature during JJA and DJF for the period 1961–2014 in China (dotted regions indicate significant correlation at the 0.05 significance level).

compound wet/cold extreme, there was a decrease at a rate of 0.01 per decade (but not significant). These results suggest that the spatial extent of the compound extremes related to warm mode has displayed an increase while that related to cold mode has presented a decrease over China during both warm and cold seasons.

3.4. Changes in the statistical distribution

For better visualization of changes in statistical distribution of spatial extent of the four compound extremes, the histogram was used here to characterize the variations during JJA and DJF in 1988–2014 relative to 1961–1987 (Fig. 5). For compound dry/warm and wet/warm extremes of the two seasons (JJA and DJF), the frequency of the large spatial extent is higher during 1988–2014 (red bins in Fig. 5) than that during 1961–1987 (blue bins in Fig. 5), indicating more areas were affected by compound dry/warm and wet/warm extremes in recent decades. For compound dry/cold and wet/cold extremes, the frequency of the large spatial extent is generally lower during 1988–2014 than that during 1961–1987, indicating that less areas were covered by compound dry/cold and wet/cold extremes during recent decades.

We further explored the cumulative distribution of the percentage area (spatial extent ×100%) of the four compound extremes during JJA and DJF for the two periods 1988–2014 and 1961–1987 using the empirical cumulative distribution function (ECDF) (Fig. 6). For compound dry/warm and wet/warm extremes during the two seasons (JJA and DJF), the upper tails of the ECDF during 1988–2014 (red lines in Fig. 6) were longer in the right than that during 1961–1987 (blue lines in Fig. 6), indicating that more areas have been affected by compound dry/warm and wet/warm extremes during JJA and DJF in recent decades. For compound dry/cold and wet/cold extremes, overall the reverse pattern was shown. The two-sample Kolmogorov-Smirnov test, a non-parametric test commonly used to evaluate whether two datasets have the same statistical distribution (Mazdiyasni and AghaKouchak, 2015; Sharma and Mujumdar, 2017), was used here to test differences of the ECDF of the percentage area of compound extremes. Except for the compound wet/cold extreme in DJF, the distributions of the percentage area of other compound extremes were significantly different during 1988–2014 compared to that during 1961–1987 at the 0.05 significance level. These results indicate that more areas were covered by compound dry/warm and wet/warm extremes while less areas were covered by compound dry/cold and wet/cold extremes for both seasons during recent decades.

4. Discussion

Previous studies have shown increased warm days and decreased cold days over China (Wu et al., 2017; Shi et al., 2018a, 2018b). Results from this study (i.e., a significant increase in the compound extreme related to warm-mode and a decrease in that related to cold-mode for the two seasons) are roughly consistent with the findings in previous studies. Though regional discrepancies of changes in precipitation exist, these changes of compound extremes may be largely affected by the general increase in temperature in summer and winter in most parts of China under global warming (Piao et al., 2010; Wang et al., 2012; Wang et al., 2016; Wu et al., 2017; Shi et al., 2018a, 2018b).

In addition, the large-scale circulation patterns may also play an important role in affecting occurrences and variations of compound extremes in China. Following Lyon and Barnston (2005), we computed the correlation between the spatial extent of the four compound extremes and different climate indices to explore the influence of large-scale modes of climate variability on compound extremes in China. We chose six indices, including AO, ENSO, NAO, AMO, PDO and EA/WR, which have been shown to affect the variations of precipitation and temperature in China (Gao et al., 2017; Sun et al., 2016; Oh et al., 2017; Peng, 2018). For each season, we took the seasonal average of the climate indices for JJA and DJF, respectively, to get the summer and winter indices. Then the relationship was assessed based on the correlation analysis using Pearson correlation coefficients, which is shown in Table 1. For warm season (JJA), AMO had a positive correlation with the spatial extent of warm related combinations (i.e., dry/warm

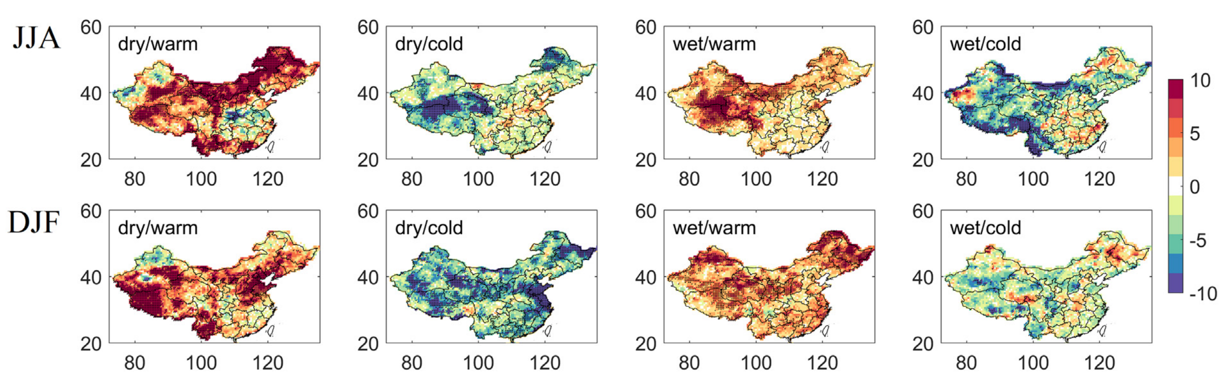

Fig. 3. Changes in the frequency (months) of compound precipitation and temperature extremes during JJA and DJF for the period 1988–2014 relative to 1961–1987 in China (dotted regions indicate significant difference at the 0.05 significance level).

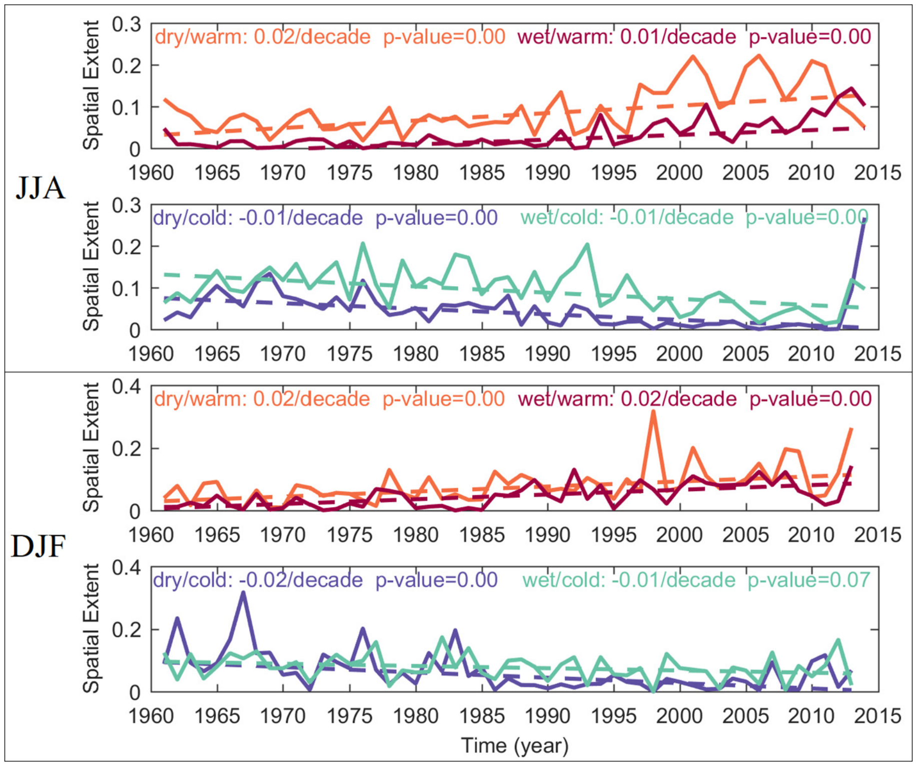

Fig. 4. Changes in the spatial extent of compound precipitation and temperature extremes during JJA and DJF for the period 1961–2014 in China (the solid lines are the annual series of spatial extent, and the dashed lines are the linear trends).

and wet/warm extremes), while a negative correlation with that of cold related combinations (i.e., dry/cold and wet/cold extremes). This indicates that more areas are affected by compound dry/warm and wet/warm extremes with a higher AMO value. For cold season (DJF), AMO was positively correlated with the spatial extent of warm related combinations. This is generally consistent with the previous studies on AMO showing significant and positive (negative) correlations with warm (cold) related indicators in the whole China (Wang et al., 2013; Shi et al., 2018b). For EA/WR, there was a negative correlation with the spatial extent of warm related extremes and a positive correlation with that of compound wet/cold extremes for JJA. Significant and negative correlations were also shown between the EA/WR and the spatial extent of compound dry/cold extremes for DJF. PDO was negatively (positively) correlated with the spatial extent of the compound wet/warm (wet/cold) extreme for JJA. NAO was negatively (positively) correlated with the spatial extent of the compound dry/warm (wet/cold) extreme for JJA. Additionally, significant and negative correlation was shown between AO and the spatial extent of the compound dry/cold extreme for DJF. This is in general consistent with previous studies that AO was an important influencing factor of climate variability in East Asia,

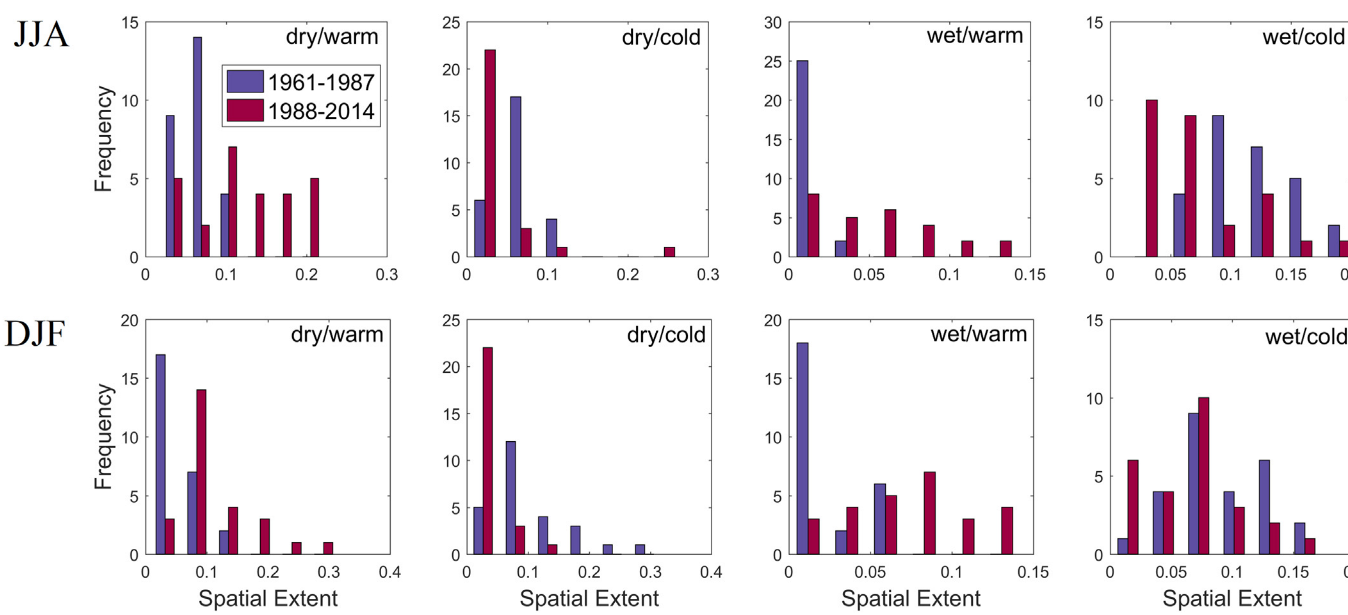

Fig. 5. Histogram of the spatial extent of compound precipitation and temperature extremes during JJA and DJF for the two periods 1961–1987 (blue) and 1988–2014 (red) over China.

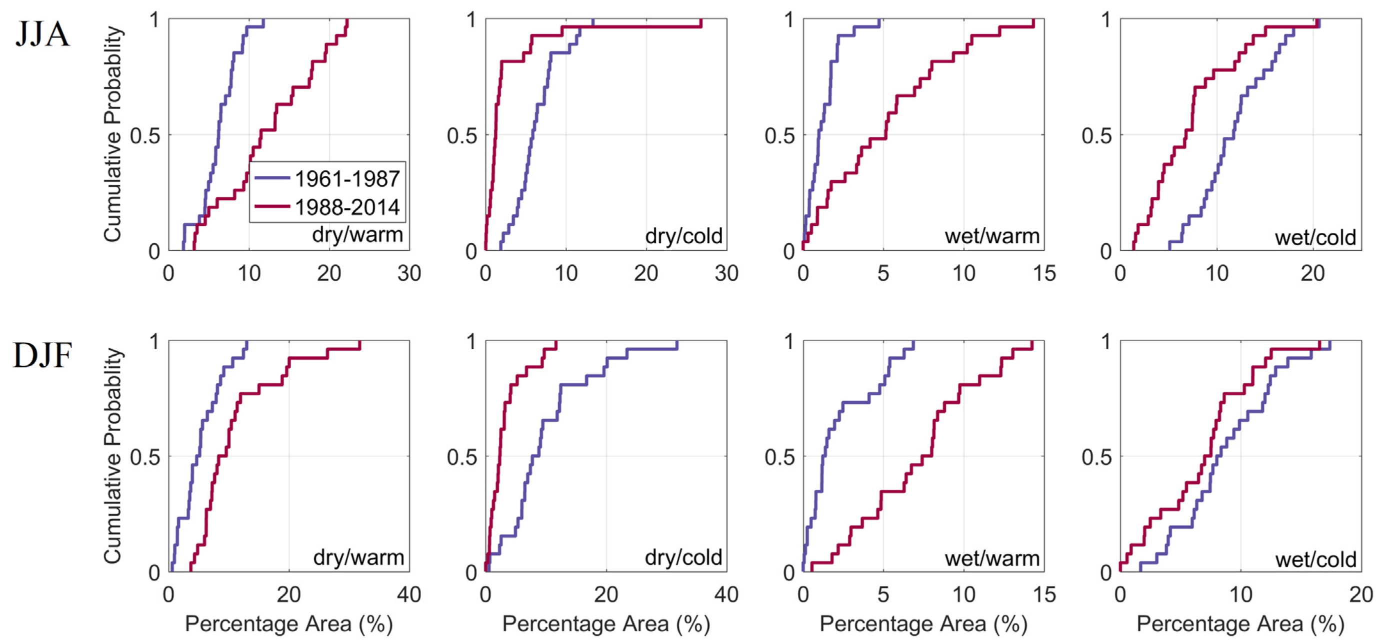

Fig. 6. The empirical CDF of percentage area affected by compound precipitation and temperature extremes during JJA and DJF for the two periods 1961–1987 (blue) and 1988–2014 (red) over China.

especially in winter (Gong et al., 2001; Lim and Kim, 2013; Song and Wu, 2018). No significant correlations were shown between ENSO and the spatial extent of compound extremes.

Results above showed that AMO had significant correlations with the spatial extent of most compound extremes for the two seasons. While for the other circulation indices, significant correlations were only shown for limited modes for certain seasons. This may be due to the reason that most of these circulation patterns mainly influence the variability of climatic patterns or extremes at a regional scale in China (Wang et al., 2008, 2018; Zuo et al., 2016). For example, the PDO has been shown to be strongly correlated with precipitation in Huaihe River valley (Wei and Zhang, 2009) and Wei River Basin, China (Liu et al., 2017). In addition, though we did not find significant correlations between NAO and the spatial extent of compound extremes in DJF, there are some studies showing its relationship with winter climate variability in some regions of China (e.g., south-central China) (Hong et al., 2008; Zuo et al., 2016). The analysis of the change in the spatial extent and its distribution showed no significant change for the compound wet/cold extreme during winter, which may be related to the absence of significant correlations between the spatial extent of compound wet/cold extreme and climate indices (Table 1).

It is worth noting that complex interaction exists between some circulation patterns, such as the interaction between the AO and ENSO (Cheung et al., 2012), as well as that between PDO and ENSO (Shi et al., 2018b), which may add uncertainties to the analysis above. Furthermore, in addition to the indices mentioned above, these spatiotemporal variations of compound precipitation and temperature extremes may be attributed to the impact of some other circulation systems, such as the Indian Ocean dipole (IOD) (Xiao et al., 2015). Therefore, more detailed and systematic investigations are required for deep understanding of the relationship between the variations of compound extremes and circulation patterns at different temporal and spatial scales.

Table 1
Correlation coefficients between the spatial extent of compound extremes and modes of climate variability in China during JJA and DJF for the period 1961–2014.

Compound extremes		Modes of climate variability					
		AO	ENSO	NAO	AMO	PDO	EA/WR
JJA	Dry/warm	−0.08	0.00	−0.35*	0.56*	−0.22	−0.40*
	Dry/cold	−0.15	0.13	0.14	−0.32*	0.12	0.20
	Wet/warm	0.06	−0.02	−0.17	0.53*	−0.31*	−0.52*
	Wet/cold	0.15	0.09	0.42*	−0.60*	0.40*	0.30*
DJF	Dry/warm	0.15	−0.05	0.13	0.31*	−0.00	−0.15
	Dry/cold	−0.30*	−0.18	−0.21	−0.06	−0.06	−0.33*
	Wet/warm	0.26	0.17	0.20	0.38*	0.07	0.12
	Wet/cold	0.01	0.08	0.14	−0.13	−0.04	0.13

* Statistically significant at the 0.05 significance level ($p < 0.05$).

5. Conclusions

This study mainly investigated the changes in frequency and spatial extent of compound precipitation and temperature extremes including dry/warm, dry/cold, wet/warm, and wet/cold combinations during summer and winter seasons in the period 1961–2014 over China. We compared the occurrences of compound precipitation and temperature extremes during 1988–2014 with that during 1961–1987 to obtain the variations of compound events. The impact of different atmospheric and oceanic circulation patterns on compound extremes was also assessed based on correlation analysis. The following conclusions can be drawn from this study:

(1) Compared to compound dry/cold and wet/warm extremes, there was a higher frequency of compound dry/warm and wet/cold extremes during both the two seasons across the whole nation. In addition, the frequency of compound dry/warm and wet/warm extremes has increased while that of compound dry/cold and wet/cold extremes has decreased for both seasons in most parts of China.
(2) The spatial extent of compound dry/warm and wet/warm extremes has presented a significant increase while that of compound dry/cold and wet/cold extremes has shown a decrease over China. The significant increase in the spatial extent of the compound dry/warm extreme and wet/warm extreme ranged from 0.01 to 0.02 per decade during JJA and DJF across China.
(3) AMO was shown to be significantly correlated with the spatial extent of several compound extremes for the two seasons. Other circulation indices were shown to affect limited compound extremes for certain seasons.

We mainly focused on the changes in compound extremes by statistical analysis. Detailed analysis of the physical mechanism of the variations of compound extremes is beyond the scope of this study and will be conducted in the future. This study could provide useful references and insights for designing response strategies for changes in compound extremes to reduce their related influences.

Acknowledgments

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